5 Comparison of UL-TOA and E-OTD Performance

This section focuses upon the accuracy and deployment of the UL-TOA and E-OTD methods for GSM mobile position location. In Table 6, the factors degrading the performance of UL-TOA and E-OTD systems are summarized.

Table 6: Summary of factors degrading performance for UL-TOA and E-OTD

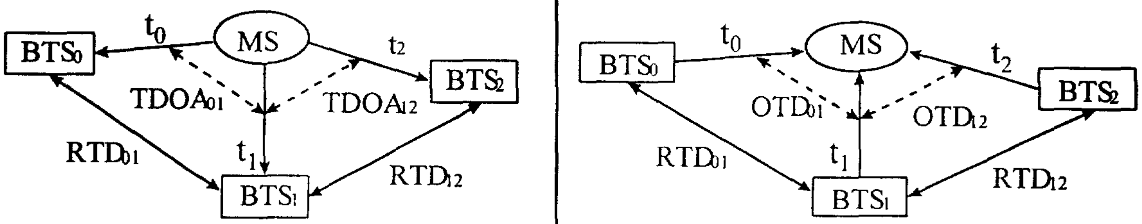
Degradation	UL-TOA	E-OTD
Multipath distortion	■	■
Noise and Interference	■	■
Clock Instabilities	■	■
Implementation sources of error	■	■
Basestation Geometry (HDOP)	■	■
RTD sources of error		■
No benefit from antenna diversity		■
No benefit from frequency hopping		■
No benefit from radio motion in RTD link		■
Does not function in areas with repeaters		■
Limited signal processing capability in the handset		■

- **There are more potential sources of error in E-OTD compared to UL-TOA.**

5.1 Performance Issues Common to Both Systems

UL-TOA and E-OTD are both fundamentally time-difference-of-arrival (TDOA) radiolocation systems. Both perform hyperbolic multilateration based upon propagation delay differences measured between link pairs taken from three or more radio links. Figure 3 shows the location calculations of the UL-TOA and E-OTD methods. For each system, estimation of the mobile location relies upon the computation of the Geometric Time Difference (GTD). Both systems establish their common timebase through the computation of the Relative Time Difference (RTD). The RTD subtracted from the observed time difference yields the Geometric Time Difference (GTD) necessary for multilateration.

UL-TOA Location Solution | **E-OTD (DL-TOA) Location Solution**



UL-TOA Location Solution

$$\text{UL-TDOA}_{ij} = \text{RTD}_{ij} + t_i - t_j = \text{RTD}_{ij} + \text{GTD}_{ij}$$

TDOA_{ij} = time of arrival difference of access bursts received at measurement units at BTS_i and BTS_j from the MS

RTD_{ij} = real-time difference between measurement units at BTS_i and BTS_j (approximately zero with GPS clock at all BTS's for timestamp of TOA data)

GTD_{ij} = geometric time difference between BTS_i and BTS_j ($=t_i - t_j$)

t_i = one way propagation time from BTS_i to MS

E-OTD (DL-TOA) Location Solution

$$\text{OTD}_{ij} = \text{DL-TDOA}_{ij} = \text{RTD}_{ij} + t_i - t_j = \text{RTD}_{ij} + \text{GTD}_{ij}$$

OTD_{ij} = observed time difference of sync., normal, or dummy bursts from BTS_i and BTS_j measured by the MS

RTD_{ij} = real-time difference between BTS_i and BTS_j

GTD_{ij} = geometric time difference between BTS_i and BTS_j ($=t_i - t_j$)

t_i = one way propagation time from BTS_i to MS

Figure 3: Comparison of UL-TOA and E-OTD Solutions

The figure illustrates that the UL-TOA and E-OTD systems are uplink/downlink duals of each other. This reveals the important conclusion that if RTDs of the two methods are equal and common assumptions are applied (i.e., uplink and downlink use the same signal), channel reciprocity dictates that the position estimate accuracy obtained by the two methods is identical. When implemented in the GSM system, however, these assumptions are not met, and the location accuracy achieved can be substantially different. In summary,

- **The UL-TOA and E-OTD methods are uplink/downlink duals of one another.**
- **Differences in performance between UL-TOA and E-OTD arise from uplink/downlink burst waveform differences, the ability to use diversity and frequency hopping, and the accuracy of the timebases derived for each method.**

5.2 Link Level Performance Differences

5.2.1 Uplink / Downlink Signal Differences

In both proposed GSM positioning solutions, time of arrival estimation is performed by cross correlating received bursts with known sequences of bits embedded in each TDMA slot. These known sequences are present in the GSM burst structure to fulfill roles in the communication network including synchronization and signaling.

In the correlation process, the signal-to-noise ratio (SNR) is improved by coherent integration over the length of the correlation sequence. Therefore, the number of bits in the known sequence is an important determinant of the accuracy of the TOA estimate in noise and interference.

Additionally, both methods propose incoherent integration of several bursts in order to improve the sensitivity of the system such that the weak signal to/from distant cells may be reliably received.

- **The LCS link level noise performance is fundamentally dependent upon the length of known sequences in the GSM bursts used and the number of bursts integrated.**

In the UL-TOA method, three to seven LMUs are commanded to listen to the mobile at the same time. In contrast, the E-OTD LMU (assuming it contains only one receiver) must listen to each BTS transmission in turn, processing bursts from each BTS in the measurement sequentially. The time required for this process can limit the practical number of integrated bursts and links used in the E-OTD measurement. The number of integrated bursts in the UL-TOA method is limited to approximately 70 bursts by a network timer that dictates how long a mobile may transmit access bursts as part of an asynchronous intra-cell handover attempt. There is a a tradeoff in E-OTD between TDOA measurement duration and accuracy. Table 7 illustrates alternative [1,9, 10] uplink and downlink bursts and the associated SNR improvements due to correlation and burst integration and the measurement time for each.

Note that the proposed UL-TOA specification using the 88 bit extended sequence from 70 access bursts provides 37.9 dB total SNR improvement. Although a number of alternative proposals are under consideration for E-OTD, the one consisting of 24 mixed (2 sync, 22 normal) bursts appears to be the leading candidate. This provides 28.4 dB improvement, which is 9.5 dB less than for UL-TOA.

- **The UL-TOA method is more effectively able to reduce noise and interference through correlation and burst averaging than E-OTD – 9.5 dB based on the most likely E-OTD specification.**

- **There is a tradeoff in E-OTD between TDOA measurement duration and accuracy.**

Table 7: SNR improvement and OTD measurement time for different burst scenarios for E-OTD and UL-TOA

Method	Burst	Correlation Gain[1]		Integration Gain		Total SNR Gain	Measurement Time (s)				
							Number of links [redacted]				
		bits	dB	bursts	dB	dB	3	4	5	[redacted]	
E-OTD	Sync	64	18.1	10	10	28.1	1.4	1.9	2.4	2.8	3.3
	Sync	64	18.1	20	13	31.1	2.8	3.8	4.7	5.6	6.6
	Normal	26	14.1	10	10	24.1	0.14	0.18	0.23	0.28	0.32
	Dummy	142	21.5	10	10	31.5	7.1	9.4	11.8	14.1	16.5
	Mixed[2]	64/26	14.6	24	13.8	28.4	0.33	0.44	0.55	0.66	0.77
TOA	Access	88[3]	19.4	70	18.5	37.9	0.32				

[1] Gain in noise. In interference, partial correlation reduces achievable gain.
[2] Consists of 2 sync and 22 normal bursts as typically seen on the broadcast channel.
[3] Consists of a 41 bit Training Sequence, a 36 bit data field known to the LMU, and 11 extended tail bits.

5.2.2 Use of antenna diversity and frequency hopping

Multipath propagation affects the accuracy of the TOA estimates in both systems. Multipath gives rise to dispersion in the time domain, which produces an irreducible error in the TOA estimate which can be sizable in highly shadowed urban environments. Diversity in time, space, or frequency can improve the estimate of TOA in multipath channels, especially when low mobile speed causes the channel to be strongly correlated over the measurement epoch. Diversity in time may be achieved by sounding the channel with repeated bursts over an interval that is long compared to the coherence time of the channel. Spatial diversity in the form of antenna diversity and frequency diversity accomplished through frequency hopping also provide decorrelated channel samples to the TOA estimation function, reducing the impact of multipath.

In addition to multipath improvement, antenna diversity provides an improvement in noise, with dual antennas providing a nominal gain of 3dB through the collection of twice the number of bursts. Because of handset size and complexity constraints, antenna diversity is impractical to implement in the E-OTD system.

- **The use of antenna diversity is impractical in the E-OTD system because TOA measurements are made at the handset.**

- **Although not generally required, the UL-TOA system can take advantage of antenna diversity, providing significant benefits in noise and multipath environments.**

Additionally, the UL-TOA system can benefit from frequency hopping when available to further improve the performance in multipath environments. In contrast, the E-OTD system listens to the GSM downlink broadcast channels that are not permitted to frequency hop.

- **UL-TOA can benefit from frequency hopping to improve performance in multipath environments while E-OTD cannot.**

5.3 System level performance differences

5.3.1 Establishment of common time bases

For the UL-TOA method, the RTDs correspond to the timebase difference of the clocks used at two LMUs to time-stamp the TOA measurements. For the E-OTD method, these RTDs correspond to the transmit timing difference of a pair of BTSs. These measurements are required because the GSM BTS clocks are not synchronized to a common timebase.

Therefore, a common timebase needs to be established in both the UL-TOA and the E-OTD methods. Presently, there are two proposed techniques for establishing the common timebases. For UL-TOA, a satellite-based technique using GPS is proposed. For E-OTD, a terrestrial-based technique to obtain a timebase using E-OTD LMUs is proposed [2]. These two techniques will be delineated in the following.

5.3.1.1 RTD Measurement Degradations on UL-TOA Measurements

In UL-TOA, the LMU uses a GPS receiver to provide a reference time base. Its time can, therefore, be as accurate as the GPS satellite atomic clocks except for the following two reasons: multipath and GPS Selective Availability (SA).

Assuming that the LMU locations are accurately surveyed, the LMU GPS receiver needs to see only one GPS satellite for the purpose of maintaining its time base.

Multipath propagation will be worst case in dense urban areas. Multipath propagation results in the introduction of a bias error in the GPS receiver's delay-locked loops during the transfer of satellite time to the LMU, thereby degrading timing accuracy. The multipath effects can largely be mitigated through careful deployment of the GPS LMU receiver antennas in these few suspect locations.

GPS clock Selective Availability (SA) modulation can be another source of timebase error. Through the use of GPS satellite clock ensembling techniques in the LMU GPS receivers, this can be averaged to a lower level. Because of the space-time common view of the GPS satellites at adjacent LMUs, the residual biases will be mostly correlated, and hence cancelled when the time difference is computed.

- **UL-TOA uses GPS to establish a common time base. Therefore, RTD measurements between BTSs are not required for UL-TOA and TOA measurement errors alone determine mobile location accuracy.**

5.3.1.2 RTD Measurement Degradations on E-OTD (DL-TDOA) Measurements

E-OTD technology uses a Reference Mobile (E-OTD LMU) to measure RTDs between base stations [2]. In order for RTD measurements to be useful, location of E-OTD LMUs and BTSs must be known. An E-OTD LMU makes two TOA measurements of two BTS downlink transmissions at approximately the same time. The difference of these two measurements determines the RTD between the two BTSs. These RTD measurements are transported back to the MSC/MLC or the mobile via the air interface for mobile positioning.

The RTD measurements are affected by multipath propagation in the same way as the TOA/OTD measurements are degraded. For unresolvable multipath, a TOA accuracy bias will be established in the RTD measurement that is propagation environment dependent. This can be a serious issue in that it affects the GTD measurement twice, increasing the overall mobile location error up to a factor of $\sqrt{2}$ relative to UL-TOA.

The location accuracy degradation effect due to multipath propagation in the E-OTD RTD measurements can be partially mitigated during deployment by raising the antenna height at the E-OTD LMU such that LOS propagation is achieved. This increases deployment complexity relative to UL-TOA. However, raising the E-OTD LMU antenna height to eliminate the multipath degradation in the RTD measurement can only be exploited so far. As the E-OTD LMU antenna height is increased, the achievable C/I decreases due to the radio propagation law changing from R^{-4} to R^{-2}. Therefore, the E-OTD LMU must be carefully designed and deployed to ensure that a TOA measurement for one BTS is not mistaken for a TOA of an adjacent BTS in a low C/I environment.

- **E-OTD requires over-the-air RTD timing measurements to establish a timebase synchronization.**

- **Noise, interference, and multipath similar to the OTD measurement degrade RTD timing measurements in the E-OTD system.**

- **Noisy RTD timing measurements constitute a significant additional source of error in the E-OTD method not present in the UL-TOA method, resulting in up to a 40% increase in overall location error.**

A brief discussion is in order regarding the RTD measurement update rate, i.e., how frequently the RTD must be computed. A slow RTD update rate was identified as an error source in recent E-OTD field trial reports [12, 13]. The required RTD update rate is determined by the short-term relative time and frequency stability of the base station clocks in the system, which is not regulated by the GSM specification as it was never intended to be used for high-accuracy LCS applications. The RTD update rate must be fast enough to avoid significant MS location accuracy degradation, see ref. [18] for additional details.

- **The required RTD update rate is determined by the relative time and frequency stability of the base station clocks in the system. Depending on the clock stability, the RTD update rate may become unacceptably high.**

- **The GSM specification does not dictate the short-term frequency stability of the base station clocks, and the specific performance obtained is likely to be BTS vendor dependent. To allow an acceptable update rate, existing GSM BTS clocks may have to be upgraded. See ref. [18] for additional details.**

5.3.2 LMU Deployment

5.3.2.1 E-OTD LMU Deployment Density

As described in the previous section, RTD measurements made over the air are subject to the same degradation experienced in the OTD measurement. Two TOA measurements are required for an E-OTD LMU to perform an RTD measurement. Often, one of the two TOA measurements involves the TOA measurement of the co-sited BTS. A co-sited E-OTD LMU can have its downlink TOA measurement receiver coupled into the BTS via cable. If this is the case, a TOA measurement for a co-sited BTS will not be affected by multipath propagation. When properly calibrated, this will result in a much smaller TOA measurement error. The RTD derived from two TOA measurements can have a smaller error if one of the two TOA measurements is for the co-sited BTS and the LMU is hardwired to the BTS. Therefore, RTD measurement error can be reduced with a higher E-OTD LMU deployment density. Previous documents have suggested E-OTD could be deployed at densities of 1:2 [14] or 1:3 [2]. These deployment densities will, however, require RTD measurements involving only two adjacent BTSs and do not include practical realities such as cell site planning and LMU redundancy for system reliability.

- **To reduce the impact of RTD error on the MS location accuracy, higher E-OTD LMU deployment density is desired.**

- **To minimize MS location error due to RTD measurement errors, real-world deployments will likely require E-OTD LMU deployment density ranging from 1:2 to 1:1.**

5.3.2.2 UL-TOA Remote LMU Deployment

Both UL-TOA and E-OTD form position estimates from intersecting hyperbolas with loci determined by the Geometric Time Differences, so the solution geometry impacts both systems similarly. The effect of system geometry is quantified through the Horizontal Dilution of Precision (HDOP[3]), which is defined as the ratio of the RMS position error to RMS range error. HDOP determines how much the ranging errors are magnified by the system geometry. In general, a geometry in which the constituent links have a large angular span have a low HDOP, and a geometry in which the links are co-linear (such as highway corridors or border areas) produce high HDOP.

The only solution for poor geometry is to modify the location system deployment. In E-OTD, location accuracy depends on the geometry of base station locations. To optimize location accuracy, one must add or move base stations. In UL-TOA, location accuracy depends on the geometry of LMU locations. Therefore, in UL-TOA, LMUs can be located as needed to eliminate poor geometry. In general, with UL-TOA, LMUs may be placed independent of base stations, allowing for simultaneous optimization of both communications coverage/capacity and location accuracy.

- **The proposed UL-TOA LMU can be remotely deployed to provide improved accuracy in areas such as corridors with poor system geometry or at edge-of-coverage.**

5.3.3 Operation of the Positioning Methods with Repeaters

In wireless systems deployment, optical fiber or radio repeaters are used to provide cost-effective coverage extension and hole filling. Repeaters can introduce an irrecoverable ambiguity in the calculation of mobile location.

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[3] Dilution of Precision from geometry is sometimes generically termed GDOP, which includes errors in three spatial dimensions plus time. HDOP refers specifically to two-dimensional geometric errors.

For MS positioning using UL-TOA, the measurement procedure is illustrated in Figure 4 for an in-band radio repeater. It is assumed that an UL-TOA LMU will be deployed at each BTS, co-located with the BTS. BTS 1 is the base station having an associated repeater. For a MS in the coverage area of BTS 1 and its associated repeater, direct radio paths towards BTS 1 and the repeater may both exist. In this case LMU 1 can be receiving the MS via its own direct path, with delay t_1, as well as via a path relayed by the repeater, with a different delay. This creates an ambiguity problem at LMU 1.

For MS positioning using the E-OTD method, there will be a similar ambiguity problem for an MS in or near the coverage area of BTS 1 and its associated repeater. It is interesting to note that this problem is there for any repeater (radio or fiber) because the repeater and its associated BTS will use the same downlink radio frequency.

- **Repeaters introduce an ambiguity in the estimated mobile position location.**

5.3.3.1 UL-TOA Operation with Repeaters

To locate a mobile in or near the coverage area of a radio repeater, the MLC needs to command the LMUs 1, 2, 3, and R to report their TOA measurement results. In Figure 4 it is assumed that LMUs 2 and 3 can hear the MS and the UL-TOA values based upon t_2 and t_3 will be reported. If there exists a path between the MS and the repeater, then the measurement unit co-located with the repeater (LMU R) should be able to hear the MS and the corresponding UL-TOA value based on t_R will be reported. Simple algorithms can then be used to resolve the TOA ambiguity problem.

- **TOA can operate with repeaters by locating an LMU at each repeater.**

5.3.3.2 Repeater Problem for the E-OTD Method

Referring to Figure 5, with E-OTD, the measurements are conducted at a MS with reception from both BTS 1 and its associated repeater (radio or optical-fiber). When measuring the downlink of BTS 1, this MS will detect two distinct correlation peaks corresponding to the two paths. For other MS locations, the E-OTD measurement results may correspond to either a direct path between the mobile and the BTS or it may correspond to an indirect path via the repeater. In either case, the E-OTD system has no way to resolve the ambiguity.

- **There appears to be no simple solution to the E-OTD repeater ambiguity problem.**

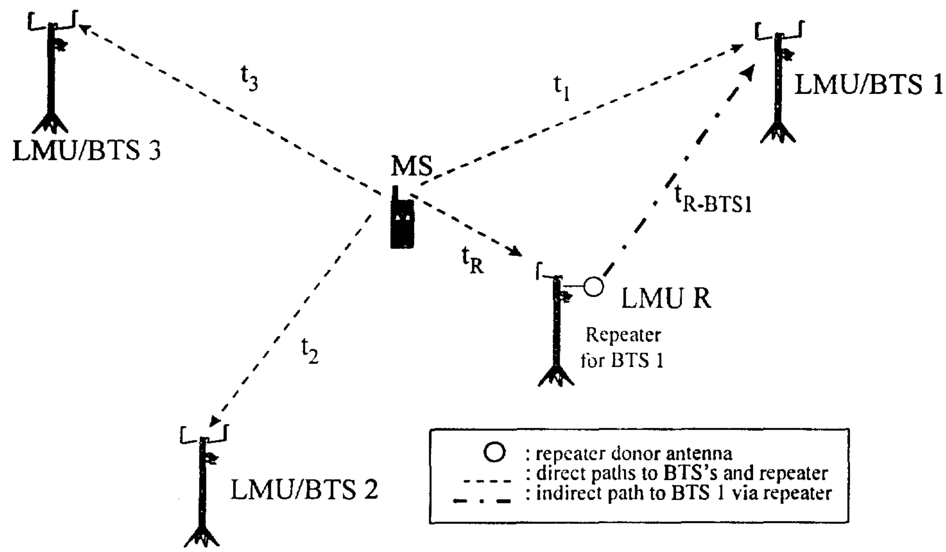

Figure 4: UL-TOA Deployment Scenario with an In-Band Radio Repeater

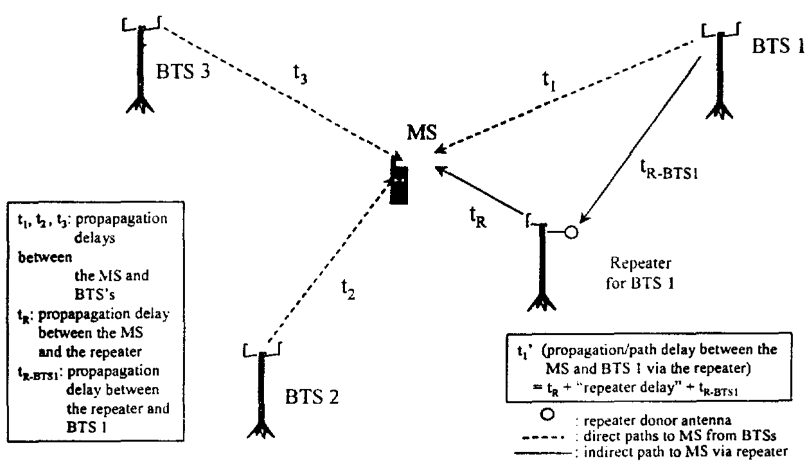

Figure 5: E-OTD Deployment Scenario with an In-Band Radio Repeater

6 Acronyms

8PSK	8-level Phase Shift Keying
A	MSC-BSC interface
Abis	BSC-BTS interface
A-GPS	Assisted GPS
ANSI	American National Standards Institute
BCCH	Broadcast Control CHannel
BSC	Base Station Controller
BSIC	Base Station Identity Code
BSS	Base Station Subsystem
BSSMAP	Base Station Subsystem MAnagement Part
BTS	Base Transceiver Station
CCCH	Common Control Channel
CDMA	Code Division Multiple Access
DL-TDOA	DownLink Time Difference Of Arrival
DL-TOA	DownLink Time Of Arrival
DTAP	Direct Transfer Application Part
E-OTD	Enhanced-Observed Time Difference
EDGE	Enhanced Data for GSM Evolution
ETSI	European Telecommunications Standards Institute
GDOP	Geometric Dilution of Precision
GGSN	Gateway GPRS Support Mode
GMLC	Gateway Mobile Location Center
GMSC	Gateway Mobile Switching Center
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communication
GSMNA	Global System for Mobile Communication North America
GTD	Geometric Time Difference
HDOP	Horizontal Dilution of Precision
HLR	Home Location Register
HSCSD	High Speed Circuit Switched Data
IMT2000	International Mobile Telecommunications 2000 System
IS-FL	Idle Slot Forward Link
IS-RL	Idle Slot Reverse Link
ITU	International Telecommunications Union
LCS	LoCation Services
Le	GMSC-External LCS client interface
Lg	VMSC-GMLC interface

Lh	GMLC-HLR interface
LMU	Location Measurement Unit
Ls	VMSC-SMLC interface
MAC	Medium Access Control
MAP	Mobility Application Part
MLC	Mobile Location Center
MS	Mobile Station
MSC	Mobile Switching Center
MTP	Message Transfer Part
NSS	Network Switching Subsystem
PCF	Position Calculation Function
PLMN	Public Land Mobile Network
PRCF	Positioning Radio Coordination Function
PSAP	Public Safety Answering Point
PSMF	Positioning Signal Measurement Function
QoS	Quality of Service
RF	Radio Frequency
RIT	Radio Interface Timing
RM	Reference Mobile
RMS	Root Mean Square
RR	Radio Resource
RTD	Relative Time Difference
SCCP	Signaling Connection Control Part
SGSN	Serving GPRS Support Node
SNR	Signal to Noise Ratio
SMLC	Serving Mobile Location Center
SS7	Signaling System No. 7
SWG	Sub-Working Group
T1P1	Network Interfaces Committee of ANSI (USA)
TA	Timing Advance
TCAP	Transaction Capabilities Application Part
TCH	Traffic CHannel
TDMA	Time Division Multiple Access
TDOA	Time Difference Of Arrival
Tdoc	Temporary DOCument
TOA	Time Of Arrival
TSG	Technical SubGroup
UL-TOA	UpLink Time Of Arrival
Um	BTS-MS air interface
UMTS	Universal Mobile Telecommunications System
VAS	Value Added Services
VMSC	Visited Mobile Switching Center

WCDMA Wideband Code Division Multiple Access

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ABSTRACT: This contribution compares the performance and complexity of the architectures and location methods that have been proposed for GSM location services. In particular, the NSS and BSS architectures are considered along with the UL-TOA and E-OTD location system methods. The performance and complexity comparisons are made in such a way that the issues associated with the technology choices become clarified.

CERTIFICATE OF SERVICE

I, Dean R. Brenner, do hereby certify that a true and correct copy of the foregoing "Comments of QUALCOMM Incorporated" was served by mail this 27th day of September 2000, to:

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